



# ***SPHERES***

## **SPHERES-X: a Proposed Inspection Laboratory Outside ISS**

Alvar Saenz-Otero

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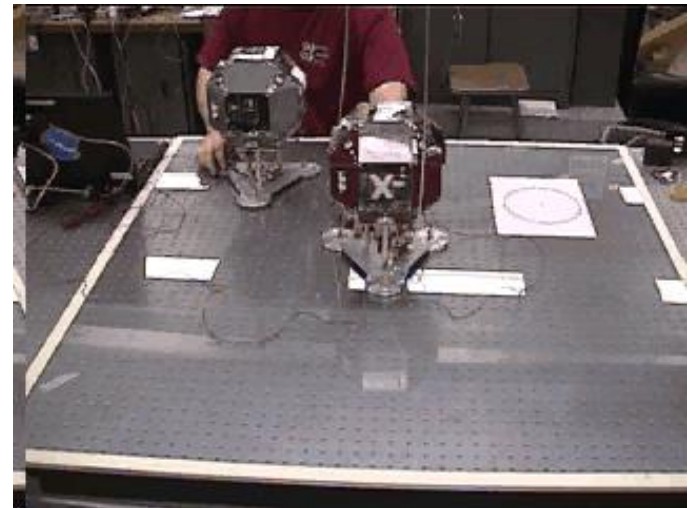
- Quick look back at current SPHERES
  - *Operations*
  - *Design philosophy*
- Motivation for autonomous robotic satellites
- SPHERES-X Requirements
  - Combine motivation and design philosophy
- Preliminary design concepts
- Preliminary mission concept



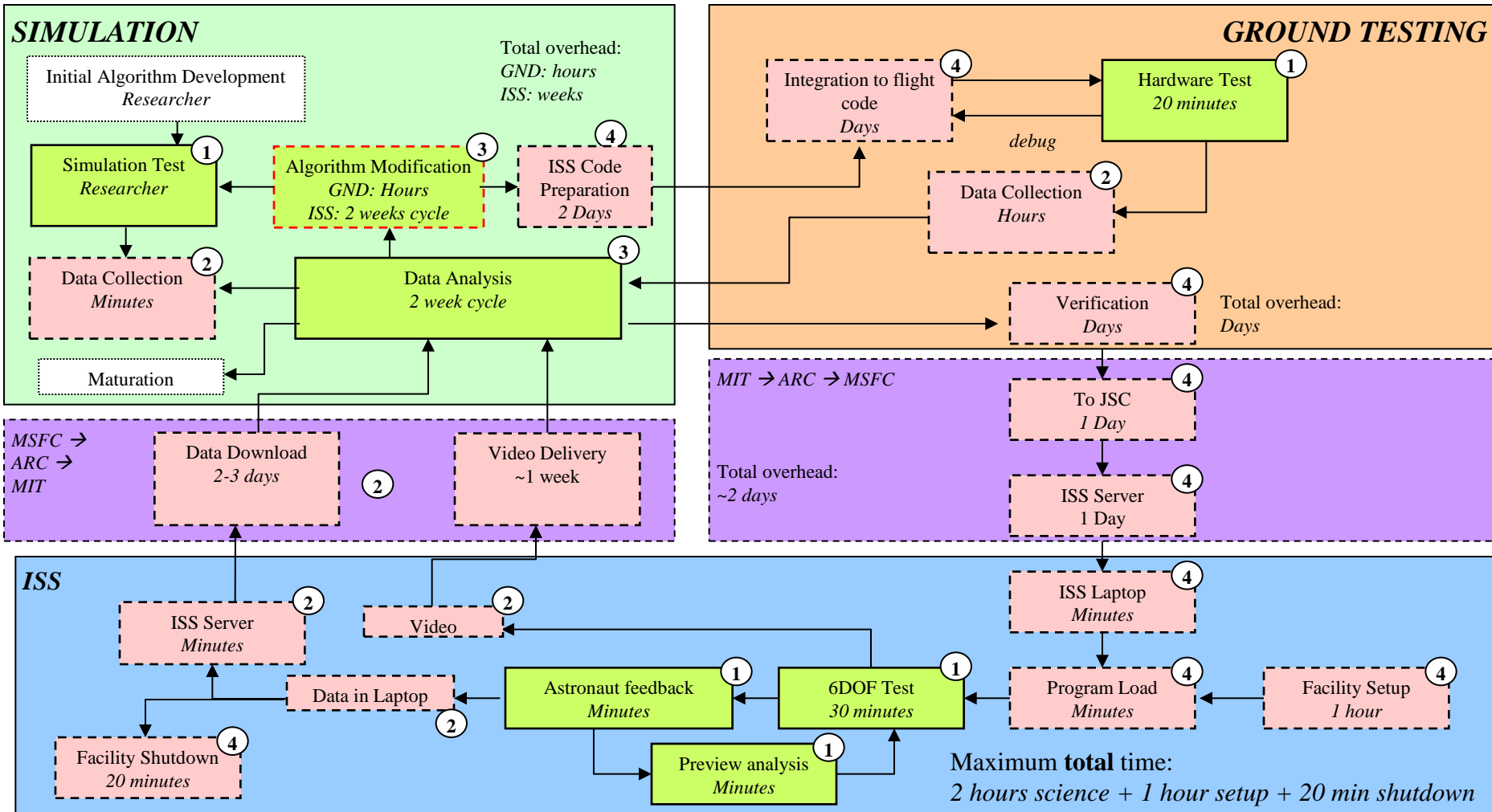
- SPHERES began as an undergraduate class at MIT, the first “CDIO Capstone”
  - Conceive, Design, Implement, Operate
- Design process applies to a facility:
  - Conceive
    - Research topics: Determine the major topics that want to be studied through this facility
  - Design
    - Research functions: Determine the research functions that the facility enables in order to provide the information to investigate the desired topics
  - Implement
    - Facility characteristics: Ensure that the facility design provides the capabilities for successful research in the selected topics
  - Operate
    - Have a set of initial operations ready to validate the facility operations

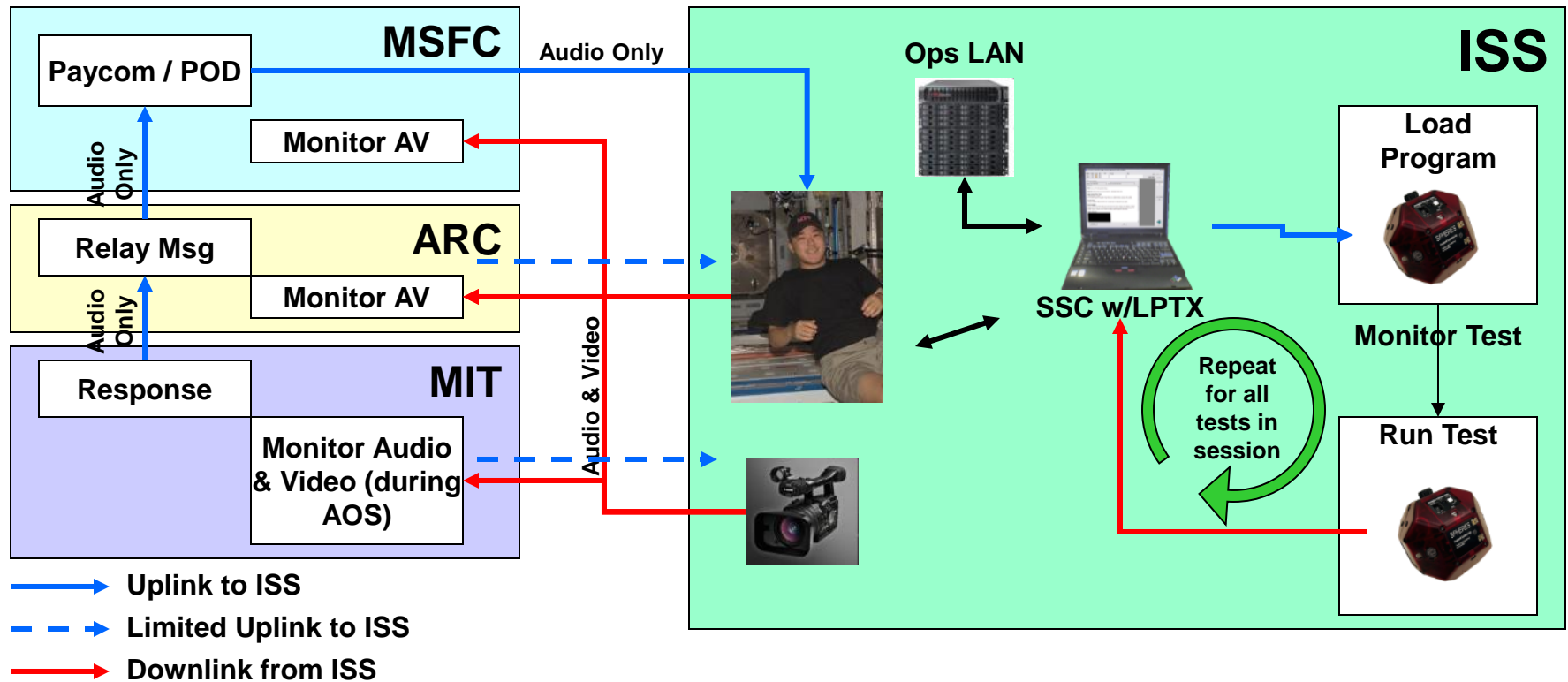


- KC-135 Reduced Gravity Airplane
  - Full 6DOF dynamics
  - Short duration
- Tests Performed (2001-Feb and 2001-Mar)
  - System checkouts
  - Single SPHERE attitude control
  - Master/Slave formation flight
- 2D Laboratory Experiments
  - Long duration 2D tests (3DOF)
  - Can use fixed supplies instead of consumables
  - Preliminary low-cost testing prior to KC or ISS deployment
- Tests Performed
  - Master/Slave formation flight
  - Docking algorithms



<http://ssl.mit.edu/spheres/videos/kc/>





- During a test session crew controls the satellites:
  - Step 1: Setup the work area
  - Step 2: Load a program into the satellites

- Step 3: Run & monitor the test
- Step 4: Move to next text based on Test Plan or feedback from the ground (if available)

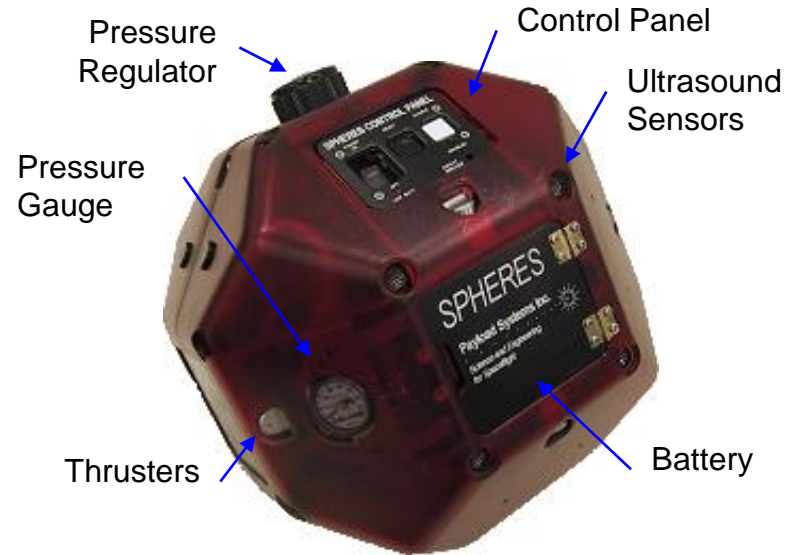
- The following seven principles capture the *underlying and long enduring fundamentals that are always (or almost always) valid* for space technology maturation laboratories:
  - Principle of Iterative Research
    - A laboratory allows investigators to conduct multiple cycles of the iterative research process in a timely fashion
  - Principle of Enabling a Field of Study
    - A laboratory provides the facilities to study a substantial number of the research areas which comprise a field of study
  - Principle of Optimized Utilization
    - A well-designed laboratory considers all the resources available and optimizes their use with respect to the research needs
  - Principle of Focused Modularity
    - A modular facility identifies those aspects of specific experiments that are generic in nature and allows the use of these generic components to facilitate as yet unforeseen experiments. Such a facility is not designed to support an unlimited range of research, but is designed to meet the needs of a specific research area
  - Principle of Remote Operation & Usability
    - A remotely operated laboratory, such as one which operates aboard the ISS, must consider the fact that remote operators perform the everyday experiments while research scientists, who do not have direct access to the hardware, are examining data and creating hypotheses and experiments for use with the facility
  - Principle of Incremental Technology Maturation
    - A successful ISS laboratory for technology maturation allows technology maturation to transition smoothly between 1-g development and the microgravity operational environment in terms of cost, complexity, and risk
  - Principle of Requirements Balance
    - The requirements of a laboratory are balanced such that one requirement does not drive the design in a way that it hinders the ability to succeed on other requirements; further, the hard requirements drive the majority of the design, while soft requirements enhance the design only when possible

- Autonomous inspection of vehicles in space
  - Enable near-field situational awareness for both manned and unmanned vehicles
  - Demonstrate (TRL7+) rendezvous to both known and unknown objects and collect inspection (visual and other sensors) data
  - Reduce need for crew EVA, especially during inter-planetary travel (high radiation environments)
  - Identification (mass properties) of unknown bodies, such as tumbling asteroids
- Space Debris Mitigation
  - Demonstrate (to at least TRL7) mechanism to capture space debris in a full, but controlled, space environment
- Sample return missions
  - Demonstrate (TRL7+) capture mechanism for sample “shot” from other bodies (e.g. Mars Sample Return)
- Continue “Distributed Satellite Systems” Research
  - Fractionated spacecraft demonstrations
  - Large space telescopes in GEO and beyond
  - Enable in-space assembly of large space vehicles (e.g. interplanetary or telescopes)



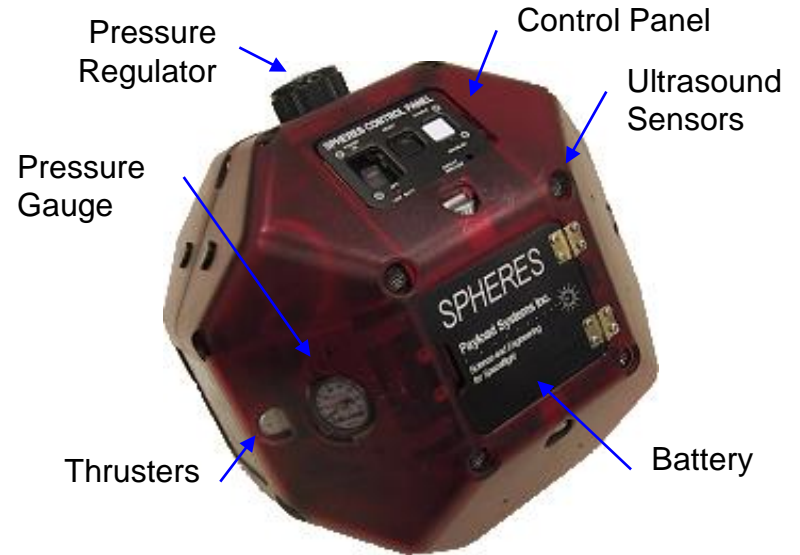
- Allow iterative research
  - REQ: scientists must be able to test their algorithms and/or hardware multiple times
  - REQ: flexible science development time
- Enable a field of study
  - Find common areas for *Inspection & Servicing, Debris Mitigation, Sample Return, DSS (Fractionated Spacecraft, In-Space Robotic Assembly)*
  - REQ: enable proximity operations
  - REQ: docking mechanism
- Optimize Utilization of ISS Resources
  - REQ: use ISS power & communications as much as possible
  - REQ: use crew inside ISS to mitigate risks and enable a risk-tolerant environment
- Modularity
  - REQ: create the basic satellites as generic satellite buses
  - REQ: ensure at least one “expansion port” is available to scientists
- Remote Operations
  - REQ: provide sufficient data to allow scientist to be virtually present
  - REQ: crew is both a local and remote operator
- Incremental Technology Maturation
  - REQ: allow scientists to concentrate on their specific technology (control cost & complexity)
  - REQ: a science failure should not mean mission failure (control risk)

- Structure: aluminum & Lexan
- Propulsion: CO<sub>2</sub>
  - liquid in tank @ 860psi
  - gas thrust @ 25psi
- Power: 16 AA Batteries
  - disposable
- Processing: TI DSP C6701
  - 166MHZ, up to 1GFLOPS
  - 16MB RAM, 256kB FLASH
- Metrology / Sensing
  - Infrared/Ultrasound “global” metrology system
  - 6 DOF IMU
- Communications: 868MHz custom RF system
  - 20kbps effective data rate
- Software: TI DSP BIOS
  - Real-time Operating System, multi-threaded, multi-priority



**SPHERES nano-satellite**

- **Structure:** aluminum & Lexan
- **Propulsion:** CO<sub>2</sub>
  - liquid in tank @ 860psi
  - gas thrust @ 25psi
- **Power:** 16 AA Batteries
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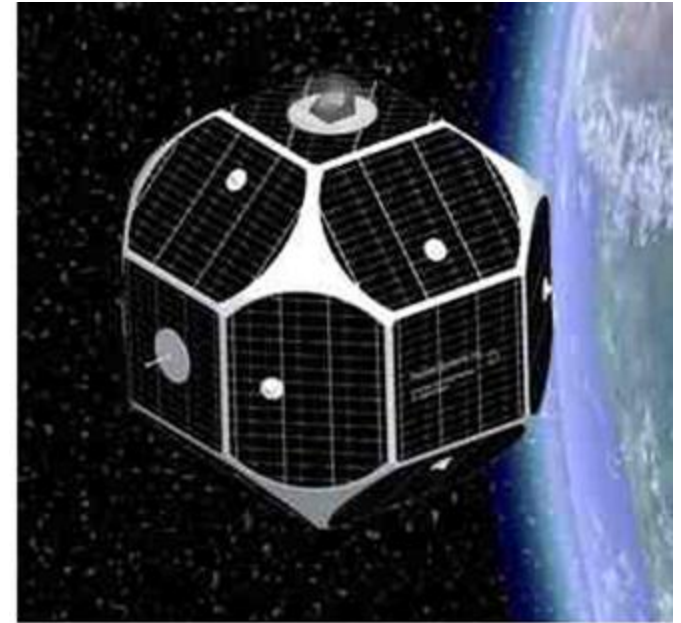
SPHERES nano-satellite



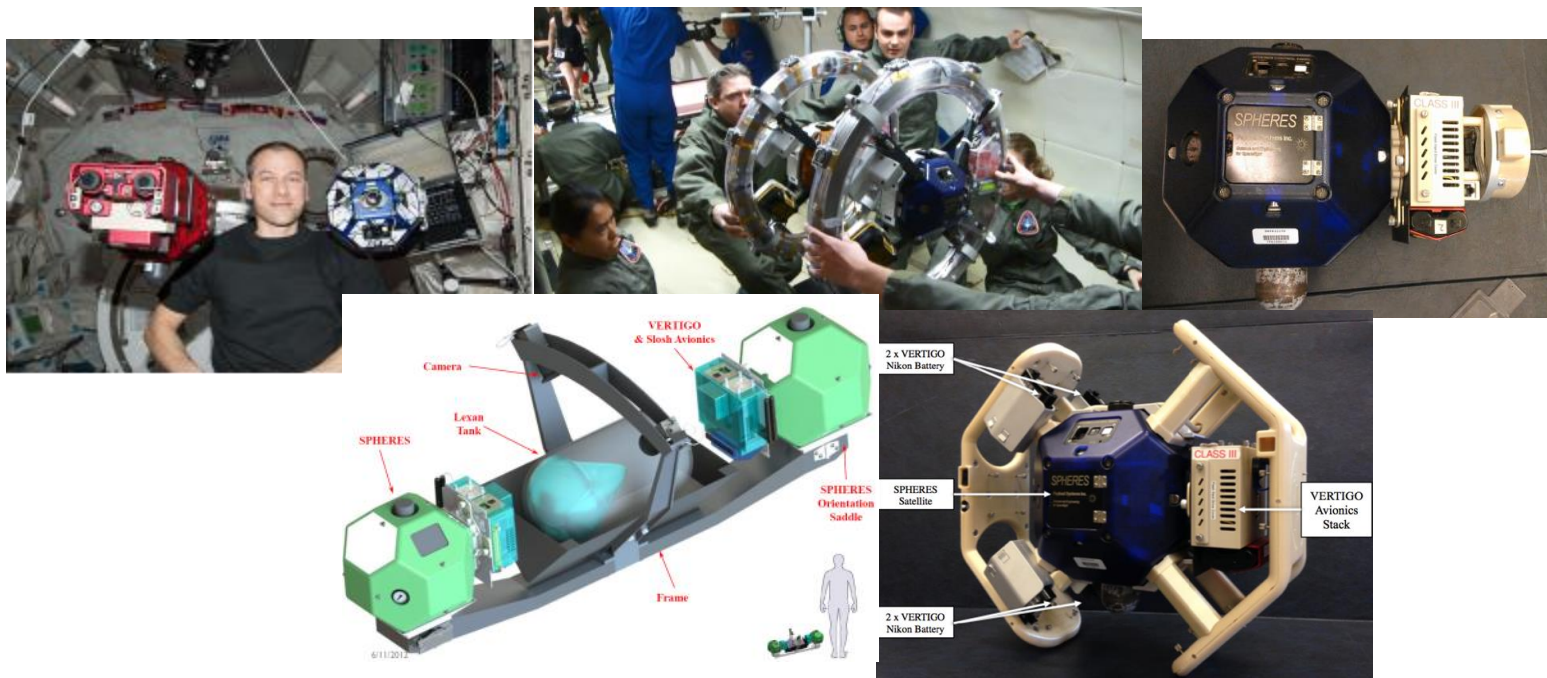
# SPHERES

## What could work?

- **Structure:** add Thermal
- **Propulsion / Actuators**
  - Nitrous Oxide, replenishable (TBC)
  - Add RWA control
- **Power: Li-Ion batteries**
  - Potentially solar panel (TBD)
- **Processing:** New CPU with RTOS
  - Multi-core system, GPU, min 1.5GHz
  - 4+ GB RAM, 128+ GB FLASH
- **Metrology / Sensing**
  - Differential GPS, cameras (6? Stereo?), LIDAR, Thermocam, Star Tracker
  - 6 DOF MEMS IMU
- **Communications:** WiFi (primary to ISS), S-band (backup to GND)
  - Potentially KU band to ISS (TBD)
- **Software:** Must still be an RTOS
  - Hard real-time interrupt capabilities, multi-threaded, multi-priority, fully customizable



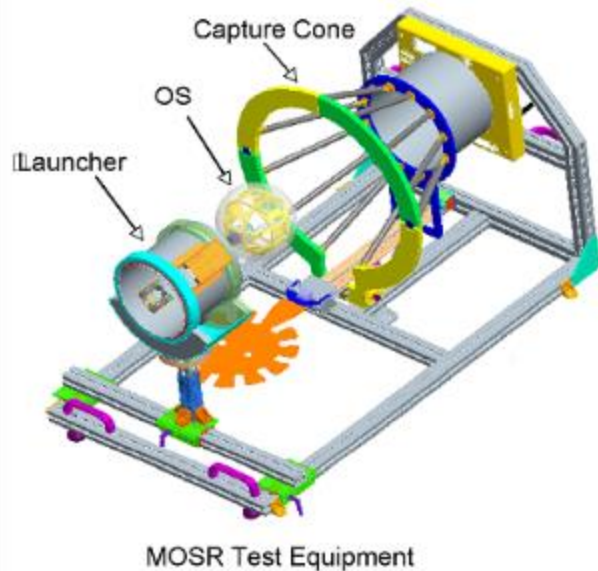
- SPHERES has a UART as the single expansion port mechanism to the DSP
- SPHERES-X need to have high-speed data lines
  - Multiple USB
  - WiFi
  - Bluetooth
- Expansion is essential to truly enable a *field of study*







- SPHERES-X Satellites must be released safely from ISS
- Use mechanism as part of the risk-reduction process
  - Create an initially “controlled” environment for the satellite release
  - Only upon satellite activating successfully within the mechanism, can it go outside
- The same mechanism is used to capture satellites upon their return
  - May not need “autonomous” recharging - *optimized utilization* may mean its easier for crew to re-supply satellites, while “autonomous recharging” is a research area!



- Must create a balance between operational safety and allowing easy scientist access to test their algorithms and hardware
- Operational safety
  - SPHERES-X team must create a set of very robust algorithms which operate the satellites while in close proximity to ISS and supervise the location at all times
  - These algorithms will require safety reviews beyond the SPHERES-X team and will not change regularly
  - It is expected that the software will require to use a Hard Real-Time operating system with high priority threads for the “supervisory control” while providing lower priority access to the scientists
- Scientist Access
  - Grow upon the concept of “SPHERES Core” where MIT provides a pre-defined API to all the common features of the satellites
  - Creates a real-time control loop (highly customizable), and provides functions for all the necessary tasks:
    - Estimation, controls, and actuation
  - Must have a **high-fidelity simulation**
    - SPHERES-X team validates based on initial operations
    - Expandable to use with custom Scientists’ hardware
  - Allow multiple levels of API access...  
could high school students use SPHERES-X one day?

**ZERO**   
**ROBOTICS**    
ISS PROGRAMING CHALLENGE



- Multiple phases with increasing complexity risk
- Phase A - Ground Testing
  - Flat floor facilities at MIT SSL
  - Reduced Gravity Flights for validation of 6DOF sensing & actuation
- Phase B - Intra-Vehicular Activity (IVA)
  - Operate SPHERES-X along-side SPHERES to validate general operation of the bus
    - Tests actuators (propulsion & RWA), relative sensors (visual, LIDAR, etc), communications (WiFi), power (batteries), processing avionics, and *software*
    - Does not test external sensors such as GPS / Star Tracker, thermal, and ground comm
  - Extensive test of “core” supervisory algorithm which controls satellite during deployment and proximity with ISS
  - Conduct initial tests of science algorithms inside ISS
  - *REQ: satellite must be operational IVA*
  - *Note: once the facility is fully operational, IVA will be repeated every time before new algorithms are tested outside*



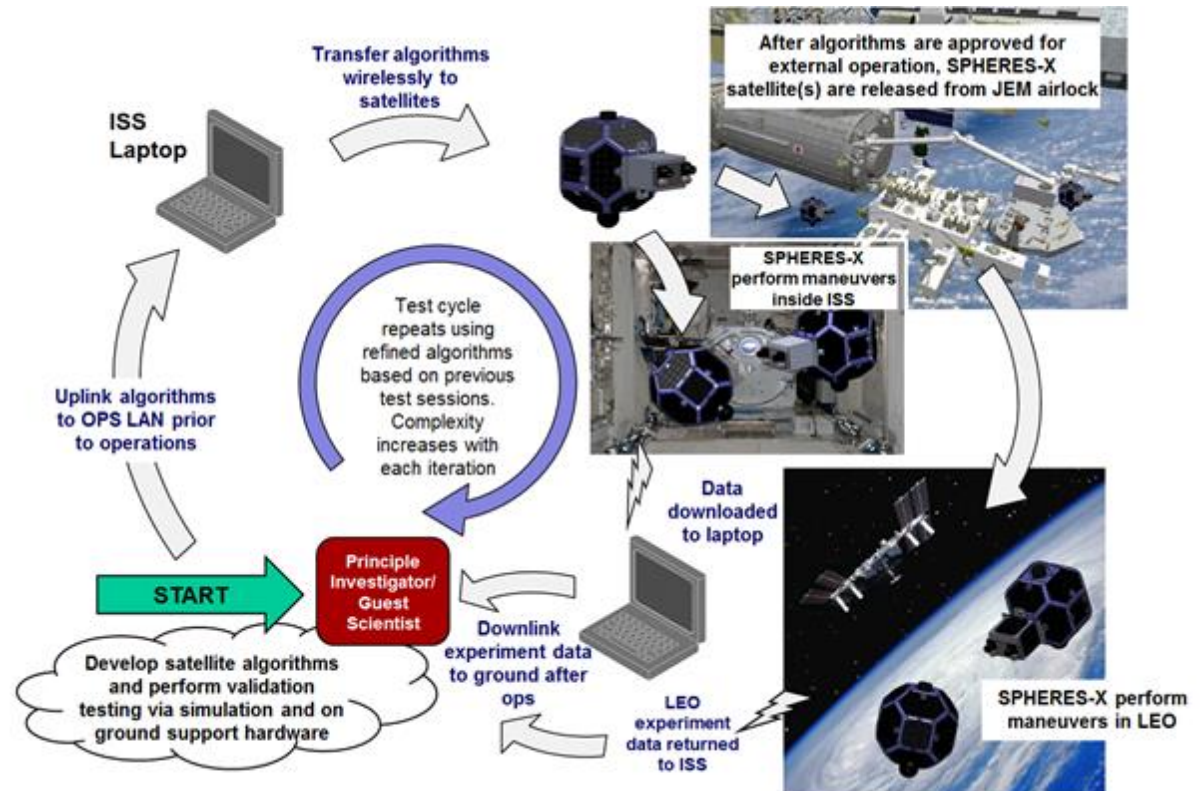
- Phase C - Captive Extra-Vehicular Activity (eVA)
  - Single satellite operated within the deploy/capture mechanism
  - Demonstrate ability to determine satellite state (sensing/estimation) and precision control (actuation) within a limited volume
  - Potentially open deploy mechanism and use ISS robotic arm to move satellite, still captured, further out
    - Only to test sensing/estimation, no actuation
  - This phase is limited to validation of the “core” algorithms for control
  - Repeat phase for up to three satellites
- Phase D - Extra-Vehicular Activity - single use
  - Upon successful deployment in Phase C, up to three satellites will be deployed to an orbit beyond their capability to return to ISS (safety distance TBD by ISS team)
  - An initial set of scientific tests will be conducted with only the base hardware
  - Objective is to demonstrate full control of the satellites, including supervisory control operation, while conducting limited science
  - *REQ: must be cost-effective to make the first set of satellites disposable*

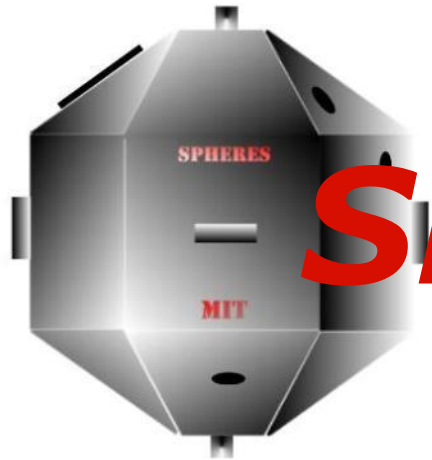
- Phase E - Free mode EVA
  - Operational facility is able to leave and return ISS under combined supervision by ground controllers and astronauts
    - Crew perform maintenance task and supervise deployment and rendezvous
    - Ground controls science operations at ISS safe distance

- Scientists are able to attach new hardware prior to deployment from ISS
  - “Open” use of SW w/ in “risk-tolerant” area

and...

- Phase F - Operations
  - It might be possible to use SPHERES-X for ISS inspection
    - Reduce ISS human EVA's





# ***SPHERES***

**Thank you!**

Questions?